Potential advantages of applying a centralized chilled water system to high-density urban areas in China

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B.S., Kansas State University, 2017

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Architectural Engineering and Construction Science
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Approved by:

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Abstract

This paper discusses the advantages of applying a utility centralized chilled water system as the district cooling choice for facilities in the high-density urban areas of China and how it will influence China's development in the next decades.

Presently, the Chinese government is trying to contribute to the world's energy-saving goals as well as determine its sustainable development framework. As air pollution has become one of the main problems in China, indoor air quality (IAQ) is likely to gain priority as a building design consideration in the future. Consistent with this fact, this paper proposes an optimum HVAC system for cooling purposes to the Chinese government.

Compared to unitary HVAC systems, the centralized HVAC system has significant advantages in system efficiency, energy reduction and cost savings and can, therefore, be a better choice. Furthermore, the paper will focus on the centralized chilled water system and demonstrate why they better match the development model in China. The application of the system in high-density urban areas will also be discussed.

Due to a lack of understanding that the energy consumption of unitary systems, the first comparison presented is between unitary HVAC systems and centralized HVAC systems in individual buildings. The comparison presented will focus on the energy-saving benefits of the centralized HVAC system in individual buildings and its contribution to sustainable development.

Consequently, prescribing a centralized chilled water system as a utility district cooling system and applying a centralized chilled water system to each individual building in the high-density urban areas will be compared. Cost savings, including initial cost and life cycle cost, are the metrics used in this comparison. Additionally, energy consumption and system reliability will be explored in determining which model will be more appropriate for China's development.

The paper concludes that the centralized chilled water system should become the mainstream in the high-density urban area in China. Several recommendations are also made to the Chinese government on setting up utility centralized chilled water systems.

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Acknowledgements

I would like to acknowledge Fred Halser as the major professor who supervised the writing this report. I am really grateful for his guidance and knowledge support on this paper. Also, I would like to express my appreciation to the committee members for their help and understanding. Finally, I would like to give special thanks to my family who supported me without complaint during this period of my life.

Dedication

I would like to dedicate this report to the time I wasted that I can never reclaim.

Chapter 1 - Introduction

Heating, ventilating, and air conditioning systems (HVAC systems), which are widely used in the United States today have become one of the essential systems for buildings constructed during the past few decades. Further, many other developed countries have also made excellent progress in HVAC system development, including those in Europe and Japan. For historical building protection, sustainable development and environment protection purposes, these countries have implemented stricter codes for HVAC systems than those prescribed in the United States. First, people need to increase awareness of the importance for HVAC systems, given the information presently available.

Goals of HVAC System

HVAC systems have become very popular because people are seeking better living and working indoor environments. Consequently, Indoor Air Quality (IAQ) has become an important consideration since it determines the nature of the air in the interior, which affects the comfort and health of the occupants. HVAC systems are required per codes and standards to achieve certain goals such as：

1. Provide sensible heating to control the space air temperature by overcoming the heat loss.
2. Provide sensible and latent cooling to offset the heat gain.
3. Provide comfortable and suitable humidity levels for the spaces.
4. Provide effective ventilation and filtration for proper indoor air quality (IAQ).
5. Provide regulation or automatic control to create the desired conditions and work.

6. Provide building/space pressurization control to limit infiltration and isolate one space from another from an HVAC perspective.

Centralized and Decentralized HVAC Systems

This paper will categorize HVAC systems as either centralized or decentralized. Further, due to its focus on chilled water systems, this paper only examines the air conditioning cooling side of the HVAC system. The following chapters make two comparisons. First, the advantages and disadvantages of using centralized HVAC systems versus unitary HVAC systems in individual buildings are compared to show why centralized HVAC systems should be used in China. Second, and more importantly, applying centralized chilled water systems as central utility plants will be compared to applying centralized chilled water systems in each individual building, which could be more appropriate to China's sustainable development.

The refrigeration cycle

The basis of the systems considered in this report utilize the refrigeration cycle. Figure 1.1 diagrams this process. Equipment used in this cycle include a compressor, evaporator, condenser, and expansion valve.

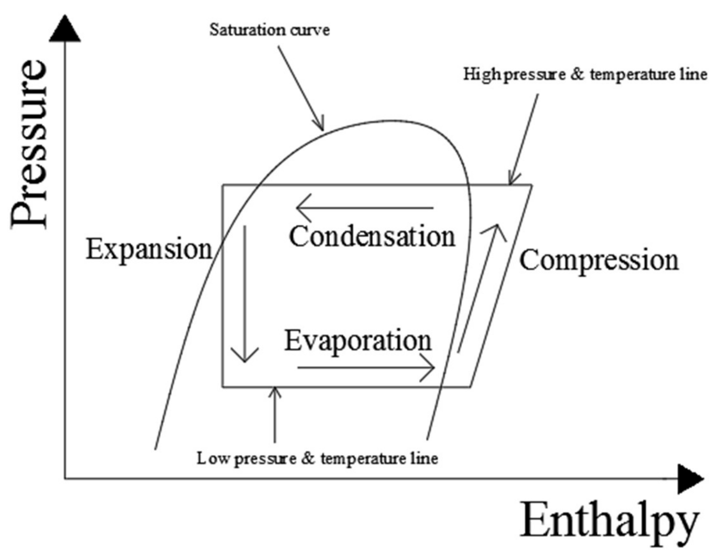


Figure 1.1 Refrigeration Cycle of Air Conditioning

The refrigeration cycle consists of four functions. The compressor increases the pressure to compress the refrigerant into a high-pressure vapor. Due to the efficiency of the equipment, the enthalpy of the refrigerant as a liquid cannot be the same as the vapors. Thus, the temperature of the refrigerant also increases. After the compression process, the condenser provides cooling, and the refrigerant vapor condenses to a liquid with the same pressure. The expansion valve continuously reduces the pressure of the refrigeration cycle and restricts the flow of the refrigeration fluid to ensure a low-pressure liquid moves into the evaporator. Finally, the evaporator absorbs outside heat and transforms the low-pressure liquid to low-pressure vapor. After the low-pressure gas flows into the compressor, the refrigeration cycle is repeated.

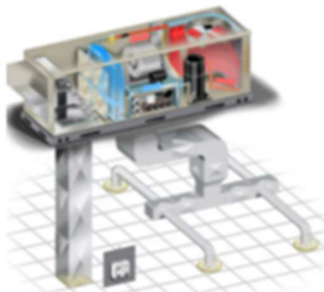
Decentralized HVAC Systems in Individual Buildings

Unitary HVAC systems are mostly direct expansion (DX) and are typical decentralized HVAC systems. These systems usually serve a single thermostatic zone or space. While many different types of decentralized HVAC systems exist, the ones most widely used in China are the following and shown in Figure 1.2:

- ✓ Packaged Window Unit
- ✓ Packaged Rooftop Unit
- ✓ Packaged Terminal Air Conditioner Unit (PTAC Unit)
- ✓ Ductless Split System

Packaged Window Unit

PTAC Unit



Packaged Rooftop Unit

Ductless Split System

Figure 1.2 Typical Unitary HVAC Systems

(Reproduced from online information and manufacture)

The advantages and disadvantages of the unitary HVAC systems must be understood. To begin with, the advantages include their small size, low initial cost, and simple installation. Second, they have independent thermostat zone controls, so they can provide customized comfort. Additionally, they do not require indoor mechanical room space, and with the exception of the packaged rooftop units, they do not require ductwork. Their disadvantages are short life expectancy, overall system efficiency, and the requirement to service and maintain many units in a single building. Furthermore, the unitary HVAC systems create more noise, have limited filtration capacity and lack the ability to process substantial amounts of ventilation air.

Due to their advantages, the unitary HVAC systems have been widely used since the 1980s in China. Their disadvantages were not considered as an important factor at that moment. Once the Chinese people realized that sustainable development was an inevitable trend, they had to consider different ways of providing heating, cooling, and ventilation to commercial properties.

Centralized HVAC Systems in Individual Buildings

Centralized HVAC systems can provide cooling to several different rooms, zones or whole buildings through the use of various methods of air delivery and heat transfer, but specifically to this report, the use of chilled water instead of unitary DX system is at the core. Also, this report only discusses conventional chiller equipment for the purpose of comparison, so the absorption chillers will be ignored. Conventional chillers, can be either water-cooled or air-cooled, and they will be the focus of centralized system comparisons in this report.

Chillers in individual buildings generate the chilled water at one location (mechanical room) in a building and distribute it to the coils in air-handling units or fan-coil units throughout the building. Water-cooled chillers reject the heat of the refrigeration cycle by connecting the condenser tube bundle to an outdoor cooling tower. Packaged air-cooled chillers are placed outdoors and contain all of the components of the refrigeration cycle. Figures 1.3, 1.5 show the major components of water-cooled chillers and Figure 1.4 is an air-cooled chiller.

Figure 1.3 Water-Cooled Chiller

Figure 1.4 Packaged Air-Cooled Chiller

Figure 1.5 Cooling Tower

Figure 1.6 is a typical water-cooled chilled water system. The chilled water system uses an indoor electric chiller consisting of a compressor, condenser, and evaporator. A chilled water pump then delivers chilled water to coils in air-handling or fan-coil equipment. The condenser water is pumped to the cooling tower to reject the heat from the refrigeration cycle.

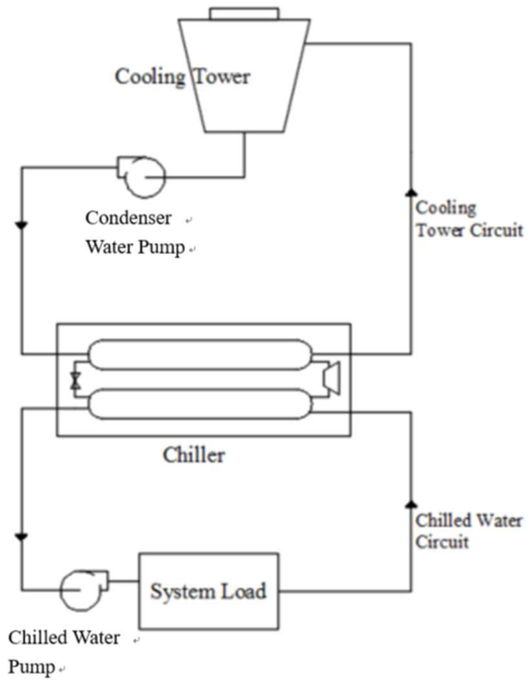


Figure 1.6 Typical Water-Cooled System Diagram

Compared to the water-cooled chilled water system, the air-cooled chilled water system is much simpler. The difference is the air-cooled chilled water system combines the condenser, evaporator, and compressors together into a single package for installation outside of the building. Figure 1.7 is a typical air-cooled chilled water system.

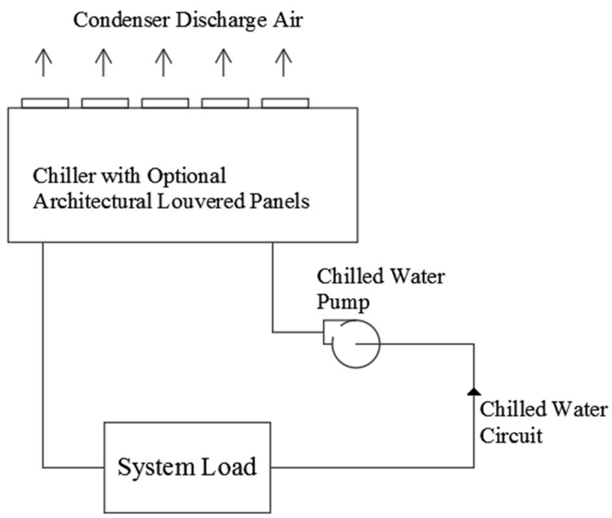


Figure 1.7 Typical Air-Cooled System Diagram

Typically, the air-cooled chillers are offered in smaller capacities. The water-cooled chillers can produce a cooling capacity in the thousands of tons. Therefore, the water-cooled chillers are usually applied in sizeable commercial buildings and requires significant floor space.

HVAC Systems in China

As the largest developing country in the world, China is trying to catch up with the developed countries regarding HVAC systems application. However, reducing energy consumption has become the biggest hurdle that the Chinese government must overcome, and the pressure mainly comes from two sources: China's development and the responsibility that China has is the largest developing country.

The first source is intrinsic to China--it is a developing nation with the largest population in the world. Thus, considering sustainable development is important because energy sources are not unlimited. The country is also experiencing a rural-to-urban development process. In the course of this demographic change, both the total population and population in the urban areas have increased respectively. The Chinese government's statistics show that people living in urban areas of China numbered around 450 million in 2000. This number increased to 660 million in 2010. The expansion of building construction in urban areas followed this population growth. According to a report on urban development in transitional China, the developed urban areas in transitional China expanded by approximately 14,000 km^2 (around 5,405 square miles), from 2000 to 2008. However, this explosive development has caused many problems, especially environmental pollution. (Xu, 2012)

People living in the urban areas also began to pay more attention to their quality of life. The increased demand for HVAC systems in China started around 2008. The Chinese government later published a market research report in 2015, concerning HVAC systems. According to that report, the value of the HVAC system market was about 4.3 billion CNY (around 623 million USD) in 2015. The residential component consisted of 1.7 billion CNY (around 246 million USD) and has increased 47% since 2014. The commercial component, on the other hand, consisted of 2.6 billion CNY (around 377 million USD) and increased 9% that year. This data shows that the demand for HVAC systems has increased significantly, and will continue to increase in the near future.

Additional pressure comes from outside China. The Chinese government has to comply with the United Nations Climate Change Conference (UNFCCC) agreement, as global warming has become an increasing concern around the world. The United Nations Climate Change Conference was first held under the Berlin Mandate in 1995. At first, it was meant to apply only to developed countries. In 2009, China joined the conference in Copenhagen, Denmark, entitled the "Copenhagen Accord." During this conference, China promised that it would reduce its carbon dioxide emissions from 40% to 45% by 2020. Unlike developed countries; China lacks the expertise and techniques to control energy consumption effectively. On the flipside, many other nations hope China, as the largest developing country, can make enormous contributions to carbon dioxide emissions reduction. As the result, the Chinese government has to create a plan for developing HVAC systems in China that will enable it to achieve its energy reduction goals.

In addition to the pressures of needing to reduce the energy consumption, China also faces an economic crisis. The economic development of China in the past several years mostly depended on the construction of commercial and residential buildings. However, as the real estate market for residential buildings became saturated in many important cities, economic growth slowed. Table 1.1 from the National Bureau of Statistics of China, on the following page, shows the development of real estate during the past several years.

Year	Floor Space of Building Under Construction (10,000 Sq. meter)	Floor Space of Finished Buildings (10,000 Sq. meter)
2000	65896.92	25104.86
2001	79411.68	29867.36
2002	94104.01	34975.75
2003	117525.99	41464.06
2004	140451.39	42464.87
2005	166053.26	53417.04
2006	194786.42	55830.92
2007	236318.24	60606.68
2008	283266.20	66544.80
2009	320368.20	72677.40
2010	405366.40	78743.90
2011	506775.48	92619.94
2012	573417.62	99424.96
2013	665571.89	101434.99

Table 1.1 The Floor Space of Buildings Developed by Enterprises for Real Estate Development for Both Residential and Commercial (Data source from China Statistical Yearbook 2014)

In Table 1.1, the floor space of buildings under construction each year increased about tenfold during the past fifteen years while the rate of the floor space of finished buildings has gradually decreased since 2000. The change shows that the real estate industry has experienced an economic slump during the past several years. Many buildings remain unfinished.

The Chinese government needs to find innovative methods of construction to continue its development. The development of an optimal HVAC system is not only a challenge for the Chinese government but also has the potential to bestow many benefits on the construction industry in China.

Chapter 2 - A Brief History of Air Conditioning Systems

Although air conditioning became widely used in modern cities during the 20th century, its beginnings can be traced back thousands of years. Both ancient China and Rome invented ways to overcome hot weather. These included manually-powered rotary fans and people traveling to mountain regions via a donkey trains to escape the heat. This paper will briefly discuss the evolutionary process of the mechanical HVAC system from the 19th century.

ASHRAE

ASHRAE is the organization the HVAC industry looks to for HVAC development and application. ASHRAE publishes the most stringent and accepted standards for HVAC systems' requirements in the world today.

ASHRAE was founded in New York City in 1894 and was initially known as the American Society of Heating and Ventilating Engineers (ASHVE). In 1959, ASHVE merged with the American Society of Refrigerating Engineers (ASRE), creating the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). It has since made strides to become a global organization eliminating the reference to the American Society and becoming ASHRAE as a stand-alone acronym. As the most recognized organization, ASHRAE keeps records about milestones in HVAC systems development.

Willis Haviland Carrier

Willis Carrier (1876-1950) is referred to as the "Father of Air Conditioning." According to an introduction in Principles of Heating, Ventilating, and Air Conditioning (Howell, 2013), Carrier made many contributions to the development of air conditioning technology with his analytical and practical accomplishments. These included the following:

- In 1902, Carrier designed and tested a year-round air conditioning system that provided heating, ventilation, humidification, and dehumidification services.
- In 1904, Carrier used atomizing nozzles and developed eliminators for an air washer to control dew-point temperature by heating or cooling a recirculated water system.
- In 1911, Carrier presented a paper titled "Rational Psychometric Formulae" at the American Society of Mechanical Engineers (ASME) meeting. The paper explained most of the modern air conditioning concepts of the time, such as dry-bulb, wet-bulb, dew-point temperature, sensible/latent heat and many others.
- In 1922, Carrier invented the first centrifugal chiller.
- In 1937, Carrier and his associate, Carlyle Ashley, invented the first conduit induction system for multi-room buildings.

Other Developments

After Carrier's accomplishments, other achievements in air conditioning continued into the mid-1930s. The heat pump, electrostatic air cleaner, high-speed compressor, and odor remover were invented during this time.

Decentralized HVAC systems dominated the United States market for a very long time. The first split system was introduced by Frigidaire in 1929. Later in 1930, General Electric improved the system. In 1931, the window unit air conditioner was invented by the H.H. Schultz and J.Q. Sherman. However, its high-cost of production made it less popular commercially. This situation changed in 1947 when Henry Galson improved the window unit making it a more compact and less expensive. Later in the 1950s, packaged rooftop units became popular in commercial buildings. Multi-zone packaged rooftop units then entered the mainstream market in the 1960s. However, once consumers started demanding greater energy efficiency, the multi-zone packaged rooftop units lost favor.

In place of decentralized HVAC systems, the centralized HVAC systems for individual buildings gradually became the most popular HVAC systems for commercial applications, such as hospitals, schools, and offices. These systems included heating and central cooling plants that created hot and chilled water for use at coils within the air-handling equipment.

Development of Higher Air Conditioning Equipment Efficiency

Equipment efficiency was the main approach to creating energy savings that gradually became more important in the 1970s. In 1975, ASHRAE published the first version of Standard 90.1 which is known as the "Minimum Energy Efficiency Requirements for Buildings Other Than Low-rise Residential Buildings" today. Subsequently, energy saving concepts were considered by designers. This paper discusses some of the basic efficiency concepts required by Standard 90.1.

Energy Efficiency Ratio

The energy efficiency ratio (EER) is an index used to judge equipment efficiency on a specific piece of cooling equipment. According to ASHRAE Standard 90.1, it is the net cooling capacity in Btuh divided by the total electrical power input in watts under designated operating conditions. This index was established by the ASME and defined as 288,000 Btu in 24 hours, as the commercial one ton of refrigeration. Also, the EER is usually suitable for commercial equipment with a cooling capacity that is over six nominal tons, or 65,000 Btu/h. Equation 2.1, below, is an annotated equation used to calculate EER according to the “ANSI/AHRI Standard 550/590” from American National Standards Institute (ANSI).

$$\mathbf{EER} = \frac{\textbf{Net Capacity (Btuh)}}{\textbf{Total Power Input (kW)}} \qquad \text{(Equation 2.1)}$$

Where,

Net Capacity = Gross Capacity – Indoor Fan Motor Heat

Indoor Fan Motor Heat = $\frac{\text{Bhp x } 746(\frac{\text{Watts}}{\text{Bhp}})}{\text{Motor Efficiency}}$ x 3.414 Btuh/Watts

Total Power Input = Compressor Watts + Indoor Fan Motor Watts + Condenser Fan motor Watts

Fan Motor Input (Watts) = $\frac{\text{Actual Power Bhp x } 746(\frac{\text{Watts}}{\text{Bhp}})}{\text{Motor Efficiency}}$ x Number of Fans

Bhp = Brake Horsepower

Seasonal Energy Efficiency Ratio

The Seasonal Energy Efficiency Ratio (SEER) is another measure used to judge equipment efficiency in cooling equipment. Based on ASHRAE Standard 90.1, it is the rating of the total cooling output during its annual cooling season divided by the total electric energy input during the same period. However, it is usually applied to equipment with a cooling capacity equal to or less than six unit tons, or 65,000 Btu/h. Equation 2.2 has the following functions for the SEER calculation according to the “ANSI/AHRI Standard 210/240” from ANSI:

$$\textbf{SEER} = \frac{\sum_{j=1}^{j=8} \frac{q*(T)}{N}}{\sum_{j=1}^{j=8} \frac{e*(T)}{N}} \qquad \text{(Equation 2.2)}$$

Where,

$\frac{q*(T)}{N}$ = the ratio of the total space cooling provided during periods of the cooling season

$\frac{e*(T)}{N}$ = the electrical energy consumed by the test unit during periods of the cooling season

N = the total number of hours in the cooling season

T = outdoor bin temperature

j = the bin number, for cooling season calculations; j ranges from 1 to 8.

Integrated Part Load Value / Non-standard Part Load Value

The Integrated Part Load Value (IPLV) and Non-standard Part Load Value(NPLV) are used to judge energy consumption when the equipment is not operating at full capacity. Generally, according to the "ANSI/AHRI STANDARD 550/590," if the calculation from a single number figure of merit expressing part-load efficiency for equipment is described in this standard, it is IPLV. If not, it is NPLV. Although it is similar to the EER, it covers the whole unloading process and based on two independent variables; part load EER and part load factor (PLF). Therefore, compared with the EER and SEER, IPLV's formula is more complex. Equation 2.3, on the next page, shows the calculation of IPLV/NPLV for units rated with EER and Equation 2.4 shows the calculation of IPLV/NPLV for units rated with kW/ton:

$$\textbf{IPLV/NPLV} = \mathbf{0.01}\boldsymbol{A} + \mathbf{0.42}\boldsymbol{B} + \mathbf{0.45}\boldsymbol{C} + \mathbf{0.12}\boldsymbol{D} \qquad \text{(Equation 2.3)}$$

Where,

A = EER at 100% load

B = EER at 75% load

C = EER at 50% load

D = EER at 25% load

$$\textbf{IPLV/NPLV} = \frac{\mathbf{1}}{\frac{\mathbf{0.01}}{\boldsymbol{A}}+\frac{\mathbf{0.42}}{\boldsymbol{B}}+\frac{\mathbf{0.45}}{\boldsymbol{C}}+\frac{\mathbf{0.12}}{\boldsymbol{D}}} \qquad \text{(Equation 2.4)}$$

Where,

A = Power input in kW/ton at 100% load

B = Power input in kW/ton at 75% load

C = Power input in kW/ton at 50% load

D = Power input in kW/ton at 25% load

Development of Refrigerant

The refrigerants used in cooling equipment are usually liquid mixtures to be used in the refrigeration cycle. They have converted in the refrigeration cycle from liquid to gas and back to liquid again. During this process, they absorb heat from liquid to gas conversion and then reject heat in the gas to liquid conversion. Figure 2.2 on the next page shows refrigerant development since the 19^{th} century.

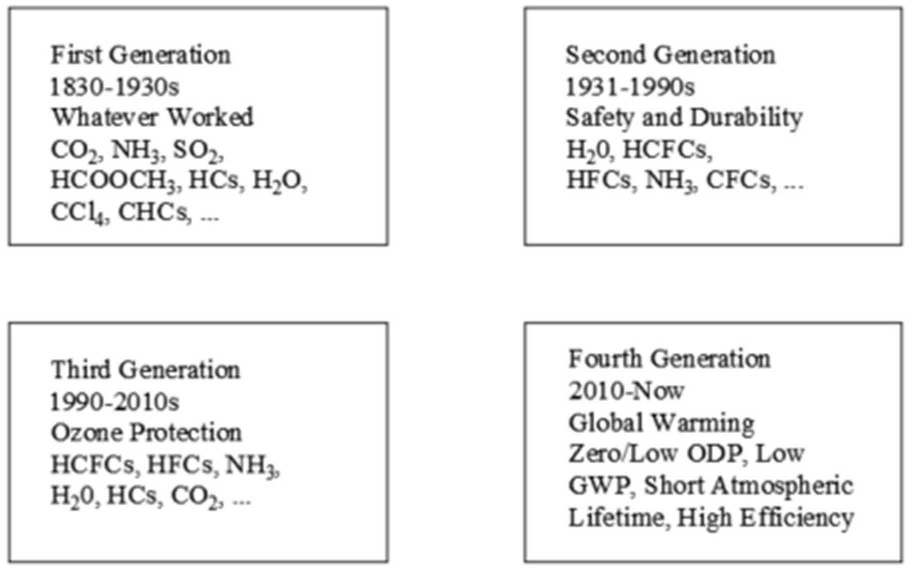


Figure 2.1 Refrigerant Development Progression (Reproduced from The Next Generation of Refrigerants- Historical Review Considerations, and Outlook, James M. Calm, 2006)

According to Calm (2006), there has been a total of four generations of refrigerants including 410-A, which are widely used in HVAC systems today.

The first generation of refrigerants was known as “whatever worked.” During the one hundred years from 1830 to 1930, these refrigerants were flammable or toxic and sometimes both. Moreover, some of these refrigerants were reactive. After conducting a series of experiments and making comparisons, Willis Carrier decided to use R-1130 (1,2-dichloroethene) for the first centrifugal machine.

The second generation of refrigerant, invented by Thomas Midgley, Jr. solved the toxicity and flammability problems associated with the first generation refrigerants. R-11 and R-12, known as Freon, have been widely used since 1931 for commercial systems. However, the R-11 and R-12 refrigerants were found to be detrimental to the earth’s environment specifically, the destruction of the ozone layer. Unfortunately, people did not realize the seriousness of this problem until the 1980s.

Consequently, R-11 and R-12 were gradually phased out through regulation, and the third generation of refrigerants were introduced. The CFC (chlorofluorocarbon) refrigerants were created to reduce the ozone depletion problem. This type of refrigerant is a mixture of carbon, chlorine, and fluorine. However, even after CFC refrigerants became widely used, global warming remained a problem.

After 2010, the fourth generation of refrigerants that have significantly less contribution to global warming were developed. Refrigerants like 410-A are new replacement products for HVAC systems. These types of refrigerants have low ozone depletion potentials (ODP) and global warming potentials (GWP). Compared to the former refrigerants, they have shorter atmospheric lifetimes and are more efficient, which is helpful to environmental protection.

China's Air Conditioning System Development

China started its development of HVAC systems very late, and the Chinese Association of Refrigeration was established in 1977. Later in 1988, the China Refrigeration and Air-Conditioning Industry Association (CRAA), the first Chinese institution for air conditioning, was established. Therefore, China only has approximately thirty years experience in serious air conditioning application.

The marketing of air conditioning and refrigeration equipment and systems has seen a significant increase since 1977. During the first ten years after the CRAA was established, around one hundred jointly owned Chinese-foreign companies were initiated. Furthermore, the industrial value of applied air conditioning and refrigeration equipment has increased from 6.5

billion CNY (around 0.94 billion USD) in 1989 to 49.3 billion CNY (around 7.16 billion USD) in 1998. In 2008, this value grew to 135 billion CNY (around 19.61 billion USD) (Liu, 2010). Moreover, the amount of residential air conditioning equipment increased approximately fifty-one times from 1989 to 1998. The number of piece of air conditioning equipment used in commercial applications increased around twenty-six times from 1989 to 1998.

However, the significant increase in the air conditioning and refrigeration market and use does not mean a significant enhancement of air conditioning technology. Although China has made significant progress on compressor development, some technologies, including installation, equipment selection, and system operation and maintenance, used in this industry in China require improvement.

Chapter 3 - Comparisons of a Centralized and Unitary HVAC Systems

This chapter examines the advantages and disadvantages of using a centralized and unitary HVAC systems. Even though many different types of centralized HVAC systems are available, the discussion will generally look a chilled water based centralized systems with air-handling units and DX unitary systems. In addition, this chapter will discuss the use of the unitary HVAC systems in China. Consequently, the advantages, and disadvantages of the centralized HVAC systems for individual buildings are stated in comparison to the unitary system, which is widely used in China today.

Centralized HVAC System Advantages

Compared to the unitary HVAC systems, using centralized HVAC systems for individual buildings have three major advantages: better indoor air quality (IAQ) control, lower life cycle cost, and a higher system efficiency.

Better Indoor Air Quality Control

Indoor air quality is a term used to describe the air quality inside of buildings and relates to the comfort and health of occupants. It can be influenced by particulates and gasses that affect human health. Compared to the unitary HVAC system, the centralized HVAC systems for individual buildings contribute to better IAQ control, which is important to China today because of the significant air pollution problem.

As air pollution becomes a serious problem, people in China also desire improved IAQ, which can create a comfortable working and living environment. With the continued industrial development, air pollution in China has become a critical problem than can no longer be ignored. According to Rohde (2015), 92% of the population in China experienced unhealthy air more than 120 hours during the period being studied, which is four months from April 5^{th}, 2014 to August 5^{th}, 2014. Additionally, air pollution has also caused 1.6 million deaths per year in China or 17% of all deaths. Consequently, the question of how to provide good IAQ in buildings is increasingly becoming more important.

The difference in filtration between the centralized HVAC systems for individual buildings and unitary HVAC systems is based on the static pressure capacity of the fans delivering air to the spaces. The air delivery systems of centralized HVAC systems can overcome a substantial pressure drop to the system while the unitary HVAC systems cannot overcome the pressure drop of high-efficiency filters. This means the centralized air delivery system can provide much better particulate air filtration.

Table 3.1 on the next page shows indoor air pollutant concentrations in buildings with different types of HVAC systems. The data are based on random measurements from thirty-seven hospitals in Taiwan.

Mean ± Std.	Indoor			
	AHU+FCU	**AHU**	**FCU**	**Window and single-split unit**
$PM_{2.5}$ (μg/m^3)	12.8±10.8	11.9±4.1	13.5±3.75	44.6±36.5
PM_{10} (μg/m^3)	21.9±10.0	22.9±5.4	28.7±2.3	59.0±34.5
	Outdoor			
$PM_{2.5}$ (μg/m^3)	23.1±25.1	18.3±8.1	18.4±4.2	52.6±42.5
PM_{10} (μg/m^3)	46.9±31.6	42.0±14.7	39.3±9.1	64.7±35.8
	Indoor/Outdoor Ratios of air pollutants			
$PM_{2.5}$ (μg/m^3)	0.71	0.71	0.75	0.87
PM_{10} (μg/m^3)	0.55	0.58	0.76	0.91

Table 3.1 Indoor and Outdoor Air Pollutant Concentrations of Buildings with Different Air Conditioning Types (Reproduced from Indoor Air Quality Varies with Ventilation Types and Working Areas in Hospitals, Chien-Cheng Jung, 2014)

Particulate matters (PM) are solid or liquid matter in the air. $PM_{2.5}$ is defined as particulate matter with an average diameter of 2.5 μm and is called inhalable particles according to the United States Environmental Protection Agency (EPA). The level of $PM_{2.5}$ becomes a concern for people's health if it becomes very high. In Table 3.1, the inconsistency in the data is a result of the statistics having come from thirty-seven hospitals. The $PM_{2.5}$ volume from the AHU, FCU, and AHU+FCU installations is much lower than that of the window unit and single-split unit applications. More importantly, the $PM_{2.5}$ value of the indoor/outdoor air pollutants ratio from AHU, FCU, and AHU+FCU applications is smaller compared to the window unit and single-split unit, which means that in the air from AHU, FCU, and AHU+FCU applications, the $PM_{2.5}$ levels are reduced. Therefore, this data shows that unitary HVAC systems, such as window type systems, do not reduce the $PM_{2.5}$ value as well as air-handling units or fan-coil units. The

PM_{10} data, which stands for the particulate matter with an average diameter of 10μm, also supports this finding.

According to Rohde's (2015) paper, China's population-weighted average exposure to $PM_{2.5}$ was 52 μg/m^3 while in the United States this number is below the US EPA's 12μg/m^3 standard for annual average $PM_{2.5}$ exposures. As a result, using centralized HVAC systems with a central air delivery method in individual buildings should be a much better choice when considering IAQ.

Lower Life Cycle Cost

Life cycle costs are the sum of both recurring and non-recurring costs over the full life span of a system. For example, the life cycle costs of HVAC systems will include the initial costs, maintenance costs, and utility costs. Usually, the initial cost of a centralized HVAC system in an individual building is higher than that of a unitary HVAC system. If owners want to replace unitary HVAC systems with centralized HVAC systems, they must make sure that the operation and maintenance cost savings can help to offset the added equipment and construction costs.

Howell (2003) examined the costs for eleven elementary schools in Las Vegas that were trying to replace rooftop DX units with systems using air-cooled chillers. These systems included an air-cooled reciprocating chiller with digital controls, hydronic loop system, chilled water pumps, and multizone air-handling units. The design team expected that the 20-year life cycle cost savings would be approximately $275,000 per school if the air-cooled chilled water systems were used. However, after studying the maintenance and utility cost savings, designers found that the actual total savings over the 20-year life cycle could be around $405,238 per school, which is 47% more than the expected life cycle cost savings. Table 3.2 summarizes these savings.

Before	**After**	**Maintenance & Operation Cost Savings for all Schools per year (Total 641,380 ft^2)**	**Savings for 20 year**
Average Maintenance Costs For the 11 Schools			
\$0.181/ft^2 per year	\$0.085/ft^2 per year	\$0.096/ft^2 per year Total: \$61,572/year	\$1,231,450
Average Electrical Costs for the 11 Schools			
59,422 Btu/ft^2 per year	50,840 Btu/ft^2 per year	Electric Price: \$0.1002/kWh Total: \$161,308/year	\$3,226,170
17.4 kWh/ft^2 per year	14.9 kWh/ft^2 per year		
Totals for Maintenance and Electrical		\$222,880/year	\$4,457,620
Average per School			
Maintenance		\$5,597/year	\$111,950
Electrical		\$14,664/year	\$293,288
Total		\$20,262/year	\$405,238

Table 3.2 Actual Operation and Maintenance Cost Savings After Retrofit with Air-Cooled Chilled Water System (Reproduced from Air-Cooled Chillers for Hot, Dry Climates, Ronald H. Howell, 2003)

According to Table 3.2, the column “before” stands for the cost for the rooftop units and the column “after” shows the data of the centralized air-cooled chiller system. The average maintenance cost for the centralized air-cooled chiller system is only fifty percent of the average maintenance cost for a rooftop unit. That saves around $111,950 for each school during the 20-year life cycle. On the other hand, although the reduction in energy consumption is only about 8582 But/ft^2 per year if the data in the “before” column minus that in the “after” column, the total utility cost saving is still $293,288 for every school over 20 years. The energy cost savings are the most important reason for applying the centralized HVAC system in an individual building. Although a comparison of these two systems will be influenced by factors that include location and the utility cost change, it shows that the energy efficiency of the centralized HVAC system is expected to be better than that of the unitary HVAC system under a similar situation.

Centralized HVAC System Disadvantages

Using centralized HVAC systems in individual buildings also has some disadvantages such as greater floor space requirements. The large physical size of the equipment and quantity of ducts and piping not only dictates that the installation of centralized HVAC systems will be complex, but also require more floor and plenum space. The result is the building's height must be increased. The Figure 3.1 shows the required heights of buildings using different types of HVAC systems.

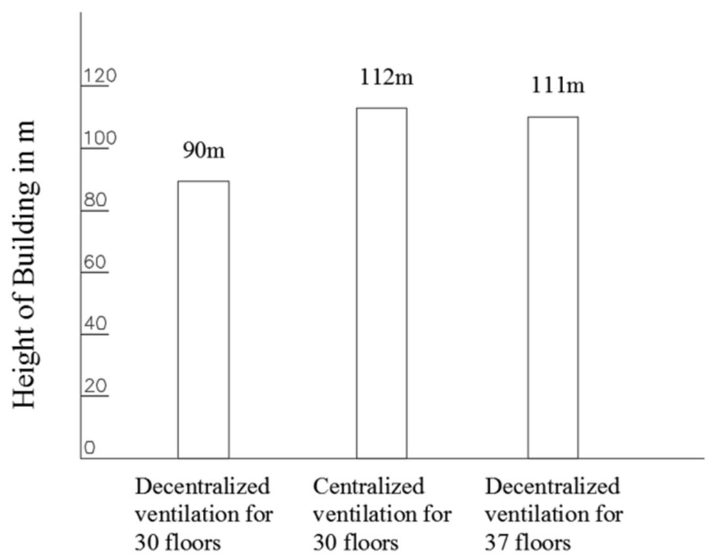


Figure 3.1 Height of a Building with Decentralized Ventilation Compared with a Building with Centralized Ventilation and Distribution (Reproduced from Comparison between Decentralized and Centralized Air Conditioning Systems, Franzke)

Figure 3.1 above indicates that a thirty-story building needs to be 112 meters in height if it uses a centralized HVAC system while a building that uses a unitary HVAC system only needs to be 90 meters in height. Similarly, if the building with the unitary HVAC system is increased to 111 meters, the building will contain seven more floors than the building with a centralized HVAC system. This means that 23% more multi-purpose usable area will be added. This additional space can offer owners huge benefits.

Summary

The comparisons in this section indicate that using centralized HVAC systems in individual buildings has some significant disadvantages. Nevertheless, these disadvantages can be easily dealt with during the design and construction process. Better IAQ control is an undisputable advantage of using a centralized HVAC system in an individual building, as it relates to human health. As long as the benefits from the energy efficiency can help to overcome the initial cost of the system, the centralized HVAC system is much better choice for the China's building -development. The benefits of IAQ control and energy efficiency should be considered when evaluating the reduction in usable space within the building.

Chapter 4 - Characteristics of Centralized Chilled Water Systems

The last chapter presented evidence that showed centralized HVAC systems are a better choice than unitary HVAC systems. This chapter will examine the major components of centralized chilled water systems. Centralized chilled water systems will be described as two major types. The first is the chilled water system for individual buildings which has already been discussed. The second is the utility centralized chilled water system, also referred to as the campus-wide chilled water system or district cooling system.

To determine if the utility centralized chilled water system is more suitable for China's sustainable development, compared to the chilled water system for individual buildings, this paper will present several advantages.

Utility Centralized Chilled Water System

The utility centralized chilled water system is widely used in many applications in the United States. This type of system locates its chillers and cooling towers in a single location and provides chilled water to several buildings around it while the centralized chilled water systems for individual buildings have the chillers and cooling towers within or immediately outside each building. Figure 4.1 diagrammatically shows a standard cooling circuit for the utility centralized chilled water system.

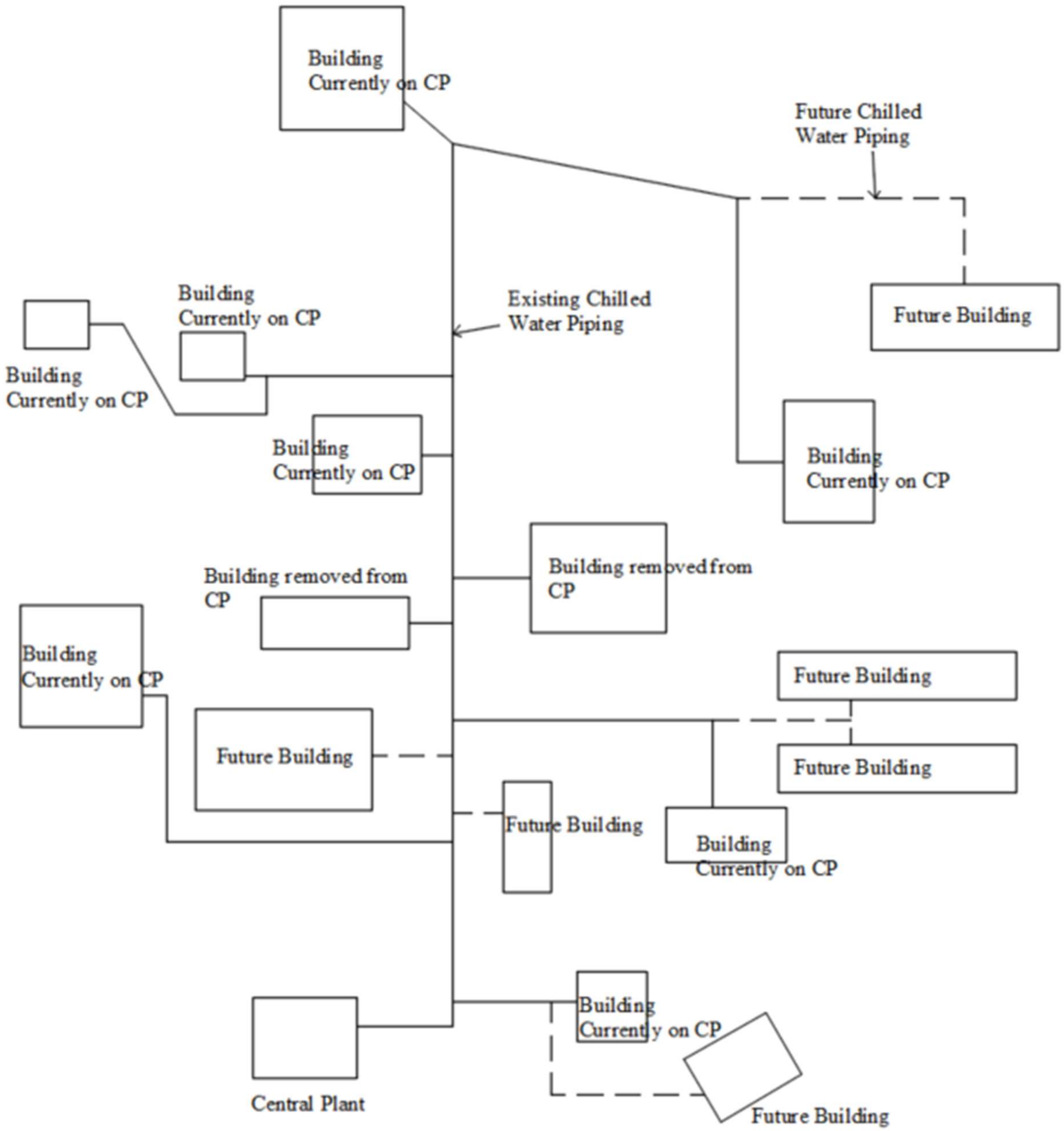


Figure 4.1 An Example of Chilled Water Distribution of Utility Centralized Chilled Water System (Reproduced from Chilled Water Plant Retrofit – A Case Study, Steven T. Taylor, Fellow ASHRAE)

The Figure 4.1 shows how different buildings are connected by the chilled water piping, with dashed line representing future chilled water piping. This means that the utility centralized chilled water system can be sized and configured to allow buildings to be added or removed from the distribution piping in the future. In addition, the chilled water produced in the central plant is available to each building as needed.

The utility centralized chilled water system can be consists of the chilled water supply and return system, and the condenser water system. This portion of the paper will focus solely on the chillers and pumping of chilled water.

Chilled Water

The utility centralized chilled water system mainly consists of water-cooled chillers, chilled water pumps, and possible a thermal energy storage tank. As the absorption chiller will not be discussed, the most common chiller is the centrifugal chiller. It can provide a range of cooling capacity up to 4,000 tons. Also, it is easy to operate and relatively quiet, and it can be applied to a design that needs a long life with low maintenance costs. The compressors in the centrifugal chiller are modulated with speed control so that the chiller can operate at partial loads to save energy.

The chilled water pumps are essential to the chilled water system. Usually, the system will have primary and secondary chilled water pumps. The function of primary chilled water pumps is to make sure that the flow of chilled water through the chillers is constant. The secondary chilled water pumps deliver chilled water to the air-handling units or fan-coil units in the buildings. The chilled water pumps most commonly used in commercial buildings are base mounted, end section, or vertical and horizontal split-case types. The factors that determine which type of pumps are to use include flow rate, head loss, efficiency, and available space.

A thermal energy storage tank is another component that is required when the building needs to shift the cooling production to off-peak hours during night time. It allows a system to collect the excess thermal energy for later use and functions, like a battery for the overall system. The system can have a significant energy cost savings because the thermal energy storage tank can collect the chilled water, from the chiller, at the off-peak electrical rates and use it during the peak electric rates. In addition, it can continue to provide chilled water to the system when maintenance of a chiller is required. Figure 4.2 is an example for how storage tank connects to chilled water system.

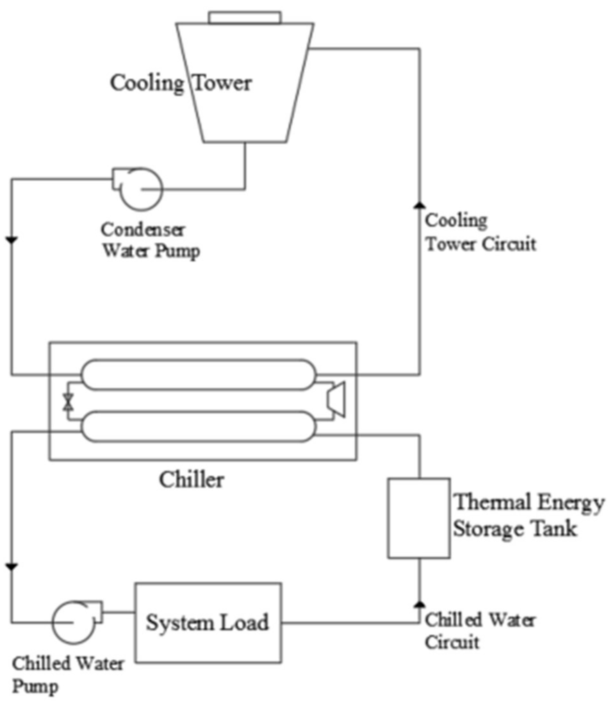


Figure 4.2 Typical Thermal Energy Storage Tank in Chilled Water System

Condenser Water

A condenser water system is used for rejecting heat from the chillers. Two different types of condenser water system are an open loop system and closed loop system. Compared to the open loop system, the closed loop system has small makeup water requirements, which is its most significant advantage. The closed loop system only needs make up water when the leakage problems occur or the system needs repair. Since all the examples in this paper are open loop systems, the closed loop system will not be discussed in detail.

For the open loop system, the condenser water system consists of cooling towers and condenser water pumps. Water is pumped from the condenser barrel of the chiller to the cooling tower. Pumps used in the condenser water loop are the same as those described for the chilled water loop.

The cooling towers can be several different configurations but the most common are cross flow, induced draft type. The capacity of these cooling towers can support anywhere from hundreds of tons to thousands of tons of chillers. Also, the materials used in the cooling tower construction play a significant role in how initial cost is determined. A significant factor in the cost of cooling towers is the use of stainless steel basin or structure.

The water makeup cost is also an important factor in the life cycle cost. However, in this paper all the chilled water systems comparisons are based on open loop systems. Therefore, both the centralized chilled water system in individual buildings and utility centralized chilled water system have makeup water requirements. The amount of the makeup water is mainly based on the cooling capacity. As the cooling capacity is most likely the same for both systems, the difference between the water makeup can be ignored. Consequently, the water make up cost won’t be discussed in the later chapters.

Advantages of Utility Centralized Chilled Water System

After having described the utility centralized chilled water system, this paper will compare the utility centralized chilled water system to the centralized chilled water system for individual buildings. The results should show why an utility centralized chilled water system is a more appropriate choice for China's development. Compared to the centralized chilled water system for individual buildings, the utility centralized chilled water system has several advantages:

1. A diversity factor can be applied when sizing and operating the equipment
2. A higher system energy efficiency
3. Lower initial, operating and maintenance costs

In this chapter, the paper will explain the first two of these advantages in detail in this chapter, and an in-depth analysis of cost will be discussed in Chapter 5.

Diversity Factor When Sizing and Operating Equipment

A diversity factor for sizing equipment is used since different buildings in the plant's cooling loop may not peak at the same time. Table 4.1 on the next page shows the system's diversity in a project that was the subject of a feasibility study for the University of Utah by Van Boerum & Frank Associates, Inc. This project concerned different buildings on campus. More information on this project will be examined in Chapter 5 in order to compare the cost savings between the chilled water systems in individual buildngs and utility centralized chilled water system.

Date	Delivered Load Tons	Connected Load Tons	Calculated Plant Diversity	Excess Tons Available
July-9	5,250	8,443	60.95%	2,750
July-10	6,552	8,443	75.45%	1,448
July-11	5,807	8,443	65.31%	2,193
July-12	5,318	8,443	70.58%	2,682
July-13	5,724	8,443	66.65%	2,276
July-14	5,713	8,443	64.25%	2,287
July-15	5,355	8,443	57.43%	2,645
July-16	5,558	8,443	66.80%	2,442
July-17	5,510	8,443	70.65%	2,490
July-18	5,872	8,443	66.08%	2,128
July-19	6,022	8,443	69.90%	1,978
July-20	5,677	8,443	64.75%	2,323
July-21	5,563	8,443	63.42%	2,437
July-22	5,981	8,443	67.63%	2,019
July-23	5,801	8,443	67.04%	2,199
July-24	5,763	8,443	77.48%	2,237
July-25	6,073	8,443	82.90%	1,927
July-26	6,491	8,443	86.15%	1,509
July-27	5,962	8,443	77.73%	2,038
July-28	5,663	8,443	68.83%	2,337
July-29	5,583	8,443	65.04%	2,417
July-30	5,747	8,443	66.61%	2,253
July-31	5,788	8,443	71.02%	2,212
Aug-1	6,808	8,443	85.40%	1,192

Table 4.1 System Diversity Study of a Campus Chilled Water Plant - July

(Reproduced from Central Campus Chilled Water Plant Feasibility Study, Van Boerum & Frank Associates Inc., 2007)

In Table 4.1, the "delivered load" column represents the daily cooling capacity use. The highest number in this column is 6,491 tons. The connected load column represents the total quantity of cooling equipment in the buildings once it is connected to the system, which is 8,443 tons. The study determined that the month of July would set the highest cooling load for the year. The table shows that the delivered tonnage in July is smaller than the total of the designed equipment capacity in individual buildings. This is because the buildings on campus won't have the peak load at the same time. In this case, the goals of the diversity factor will be met and the equipment will be sized for and operated at a smaller cooling capacity.

In high density urban areas in China, there will be more different types of facilities so the use of the utility centralized chilled water system will be even more varied. The utility centralized chilled water system has an advantage in terms of it adaptability to diverse situations, and that it can easily be used in China to accommodate several buildings of the same or different occupancies.

Higher Energy Efficiency

The utility centralized chilled water system's components are similar to those used in the centralized chilled water system used in individual buildings. The main differences in their energy efficiency results from the applied equipment, especially the chillers. Usually, larger chillers have better energy efficiencies.

According to Hua's (2009) study, the EER of a water chiller increases as the cooling capacity increases. It indicates that chillers in the utility centralized chilled water system can easily have a higher EER compared with the chillers for individual buildings. This becomes advantageous in China since the urban areas in China have large populations and many buildings that require a large cooling capacity in the district cooling system.

Disadvantages of Utility Centralized Chilled Water System

The utility centralized chilled water system has some drawbacks. The most important one is the thermal loss in the piping networks. Since the utility centralized building system consists of large-distribution piping networks, the thermal and hydraulic losses can be significant. This problem can be partially solved by using adequate or increased pipe insulation. Because the ground temperature is so close to the chilled water supply and return temperature, the thermal loss problem can easily be solved. In addition, the networks of the large-distribution piping require high-performance pumps to minimize energy consumption. This is because the pump power consumption of the utility centralized chilled water system is greater than that of chilled water system for individual buildings. However, this problem can also be ignored because the chiller power consumption reduction will offset the extra pump power consumption. This will be explained later in Chapter 6.

Chapter 5 - Potential Cost Savings of Utility Centralized Chilled Water Systems

Although chilled water systems have been used for nearly thirty years in China, the utility centralized chilled water system for high density urban areas has not been established yet. In addition, many other utility centralized chilled water system projects in some developed countries, such as the United States, Canada, Sweden, and Japan, have been planned but are still under construction. Consequently, drawing accurate conclusions about the use of district cooling systems for urban areas is difficult because of lack of data. An university campus centralized chilled water plant can be used however in a cost analysis. Both campus and urban areas have residence, commercial, and office areas. Most importantly, this kind of system has been widely applied around the world, and it is easy to obtain accurate data from well-developed projects. As a result, the data from a campus chilled water plant project in University of Utah will be used to show the potential cost saving for the high density urban areas in China.

The reason why the author chose a project at a campus in Utah is based on climate considerations. Because of the weather in Utah, the buildings do not have large cooling requirements. The cooling season in Utah is only during the summer. Then, if it is possible to prove the utility centralized chilled water system has a potential cost saving in Utah compared to the chilled water system in individual buildings, it also can be assumed that the utility centralized chilled water system has a potential cost saving and is more appropriate to those areas that have a larger cooling requirement. Table 5.1 on the next page is the climatic design information from the 2013 ASHRAE Handbook—Fundamentals.

Location	Latitude	Longitude	CCD (°F-Day)
Salt Lake City, Utah, US	40.79N	111.97W	1218
Beijing, China	39.93N	116.28E	1553
Shanghai, China	31.40N	121.47E	2138
Guangzhou, China	23.22N	113.48E	3762

Table 5.1 Climatic Design Information in Utah and Main Cities in China. (Data from the 2013 ASHRAE Handbook—Fundamentals)

In Table 5.1 CCD is the annual cooling degree-days, which is a representation of the amount of energy needed to cool buildings. A larger cooling requirement exists when the CCD number increases. According to Table 5.1, Beijing, the capital city of China, has a similar latitude with the Utah, but its CCD is higher than Utah. The CCD of Shanghai and Guangzhou becomes greater as the latitude number decreased. Therefore, most areas in China have a larger cooling requirement than in Utah. The conclusion from the project at the University of Utah can be applied to most areas in China.

This chapter will discuss two different potential cost savings. The first is the initial cost saving, which is mainly influenced by the equipment costs and labor costs. Cost savings also result from operation and maintenance (O&M) of the system. Both initial and O&M cost savings are important because while the former plays a vital role in determining whether the project is worth investing in, the latter determines when owners can expect to recover their initial investments.

Initial Cost Savings in the United States

In the 21st century, the utility centralized chilled water system has been gradually replacing centralized chilled water systems in individual buildings at many universities, such as

Yale University, the University of Michigan, the University of Houston, and others. This section will examine a project from Van Boerum & Frank Associates, Inc., which performed a central campus chilled water plant feasibility study for the University of Utah.

To replace the chilled water system at the University of Utah, Van Boerum & Frank Associates looked at two different solutions. The first option involved replace several existing chillers and building more new building chiller plants. The second one involved connecting all of the buildings in the central zone of the campus to a single chiller plant. After estimating the total cost of the two different options and considering the needs of the central plant, Van Boerum & Frank Associates determined the second option (option 2), which is the utility centralized chilled water system, was the best solution. Table 5.2 and Table 5.3 on the following pages present the initial cost saving calculations for both options and the resulting estimated cost savings

Initial Costs Summary	Individual building Chiller Plants	New Central Plant
Replace Existing Chillers (2,320 ton)	$ 1,761,375.00	
New Building Chiller Plants (6,178 tons)	$13,622,490.00	
New Central Plant (7,000 tons)		$11,319,818.00
Piping Distribution to all Existing & New Buildings Total	$15,383,865.00	$13,951,733.00
Savings for Central Plant Over Individual Chillers in Each Building		$1,432,132.00

Table 5.2 The Initial Cost Summary of Using the Centralized Chilled Water System Instead of Decentralized Solution (Data from Central Campus Chilled Water Plant Feasibility Study, Van Boerum & Frank Associates, Inc., 2007)

ITEM		Total Cost
2000-ton Chiller x2		$950,000
1500-ton Chiller x2		$735,000
Cooling Tower		$875,000
New Condenser Water Pump		$140,000
New Primary Chilled Water Pump		$104,000
New Secondary Chilled Water Pumps		$152,000
Installation of Chiller		$128,000
Installation of Pumps		$240,000
Controls for Chiller Pumps		$185,000
Piping for Pumps and Chiller		$1,550,000
Building. Including HVAC & Electrical		$1,620,000
Fire Protection in Building		$18,000
Valves		$280,000
Misc. Supports. Pads. Seismic. Insulation. Etc.		$390,000
Plumbing		$36,000
Electrical for Chiller and Pumps		$1,686,825
Site Improvements		$240,000
Water Treatment		$25,000
Contractor mark up on equipment	**15%**	$333,150
Subtotal		$9,687,975
Contingency	**5%**	$484,399
Subtotal		$10,172,374
General Contractors Fees	**4%**	$406,895
Subtotal		$10,579,269
Escalation to be added beyond Aug. 2007	**0%**	$0
Subtotal		$10,579,269
Engineering	**7%**	$740,549
Total		$11,319,818

Table 5.3 The Estimation of Initial Cost of the Option 2 New Central Plant, 7000 Tons (Reproduced from Central Campus Chilled Water Plant Feasibility Study, Van Boerum & Frank Associates, Inc., 2007)

Table 5.2 compares the initial costs of using the chilled water system for individual buildings to the new central plant. It is easy to conclude that the cost savings from the central plant over individual chillers in each building is approximately 1.43 million dollars. Table 5.3 presents estimates of initial costs for the utility centralized chilled water plant (option 2) in detail. The initial cost savings are mainly due to the utility centralized chilled water system requiring less chiller and cooling tower tonnage. Although this kind of design may require a larger piping system and higher construction costs, the equipment cost savings are significant. Also, in Table 5.2, the total design tonnage of the individual chillers in each building is 8,498 while the design utility centralized chilled water system has a total tonnage around 7,000. The reduction is a result of the diversity factor explained in the preceding chapter, which means the buildings on the campus will not peak at the same time.

Based on the cost savings for campus chilled water plant in Utah, it can also infer that the utility centralized chilled water system would be appropriate in China. First, according to the statistics from the United States Department of Labor, the average hourly compensation costs of manufacturing employees in China was around $1.75 in 2009; this number in the United States was $34.81 in 2010. In this case, China has lower labor costs than the United States, so the construction costs in China will be lower. On the other hand, because many chiller manufacturers have expanded their products to be available around the world, it is possible that the same type of chiller can be used in China that was used in the United States. The cost of equipment in China should be very close to the cost of the equipment in the United States; therefore, the cost savings resulting from the equipment will be the same. Therefore, because the equipment cost savings account for a much bigger part of the initial cost savings than the construction cost savings, the use of the utility centralized chilled water system will still, show a huge initial cost savings if the project were to be constructed in China.

Initial Cost Savings in China

Another campus chilled water plant project in China also supports the conclusion reached above. This section examines a project for a campus chilled water plant in Guangzhou, a large utility centralized chilled water system, which supplies chilled water to ten different campuses nearby. During this project, the engineer calculated the differences in land area requirements between using district centralized and individual building chiller designs. The chilled water system for individual buildings would require an additional 40,000 square meters (around 430,556 square feet) of building area beyond that required for the utility centralized chilled water system design. Table 5.4 on the next page represents the calculations the engineer used.

Stub Head Name of University	Amount of Equipment	Mechanical Room Required for Individual System (m^2)	Mechanical Room Required for Utility Centralized System (m^2)	Saving of Required Room Area (m^2)	Equipment Cost Saving (Thousand CNY)	Construction Cost Saving (Thousand CNY)	Total (Thousand CNY)
Sun Yat-sen University	50	849	150	699	14,380	1,400	15,780
Guangdong University of Foreign Studies	372	6,586	1,019	5,567	112,740	11,130	123,880
Guangzhou University of Chinese Medicine	390	7,279	1,165	6,114	129,060	12,230	141,290
Guangdong Pharmaceutical University	284	4691	628	4,063	699,60	8,130	78,090
South China University of Technology	254	5,358	851	4,507	105,990	9,010	115,000
Guangdong University of Technology	144	3,293	460	2,833	646,60	5,670	70,320
Guangzhou Academy of Fine Arts	138	2,740	406	2,334	493,70	4,670	54,040
Guangzhou University	446	9,514	1,413	8,101	136,300	16,200	152,500
South China Normal University	190	4,169	532	3,637	782,70	7,270	85,550
Xing Hai Conservatory of Music	140	1,673	288	1,385	201,50	2,770	22,920
Total	2,408	46,152	6,912	39,240	780,890	78,480	859,360

Table 5.4 Cost Saving Comparison Between Utility and Individual Chilled Water System in Guangzhou Campus Area (Reproduced Source from Wang, Zhao, 2003)

In Table 5.4, the stub head contains the names of each university. The first column contains the amount of equipment required for the individual building design. The second and third columns represent the space required for individual and utility centralized chilled water system designs, respectively. The fourth column shows the individual chilled water system room area minus the room area required in the utility centralized chilled water system, representing the room area savings. The last three columns present the equipment, construction and total cost savings for each campus, respectively. The total equipment cost savings of these ten universities is around 781 million CNY (around 113 million USD), and the total construction cost savings, which includes equipment and labor cost savings, are about 78 million CNY (around 11.3 million USD).

The two different projects in Utah and Guangzhou provide a detailed as well as a generic view of cost savings. In both cases, the utility centralized chilled water system shows substantial initial cost savings compared to using centralized chilled water systems in individual buildings.

Operation and Maintenance Cost Saving

Operation and maintenance costs are a large part of the life cycle costs (LCC) for a project. LCC savings indicate the true costs over time and can lead to an estimation of when an owner can recover the initial investment. Therefore, the O&M cost savings are an important factor in determining whether the project is financially viable. The O&M cost savings from the utility centralized chilled water system are very important for the sustainable development of China. In the study from the University of Utah, the O&M cost savings were another factor in the decision to choose the option 2. Table 5.5 illustrates the O&M cost savings expected on the Utah campus by using the utility centralized system instead of chillers in individual buildings.

O&M Costs Summary	Individual building Chiller Plants	New Central Plant
Existing O&M Annual Costs (Existing 2320 tons)	$231,970.00	
Estimated O&M Annual Costs (Existing 2320 tons)		$115,680.00
Estimated Future O&M Annual Costs (For new 6178 tons)	$617,720.00	$308,048.00
Subtotal	$849,690.00	$423,728.00
Annual O&M Savings for a Central Plant		$425,962.00

Table 5.5 The Operation & Maintenance Cost Summary of Using the Centralized Chilled Water System Instead of Decentralized Solution (Data from Central Campus Chilled Water Plant Feasibility Study, Van Boerum & Frank Associates, Inc., 2007)

In Table 5.5, the column for individual plants lists of the costs for the chilled water systems in individual buildings. The central plant is the new utility centralized chilled water system design and estimated O&M annual costs totaling $423,728. This shows total costs for the individual building plants to be almost twice as much as those for the central plant option. Table 5.6 and 5.7 show the detail of costs summarized in Table 5.5.

Existing Distributed Chillers			
Electrical Cost (2320 tons)	**Annual Electric Consumption (kw-hrs)**		**Total Costs**
Chiller Totals	1,749,785	0.048$/kwh	$83,990
Pump Totals	255,202	0.048$/kwh	$12,250
Cooling Tower Totals	177,725	0.048$/kwh	$8,531
		Subtotal	$104,770
Maintenance Cost			
U of U personnel	1.25 man-years	$60,000/year	$75,000
Vendor Maintenance	2,320 tons	$22.50/ton/year	$52,200
		Subtotal	$127,200
		Existing Distributed Chiller Annual O&M Costs	$231,970
		Cost/ton/year	$99.99
		Estimated cost per year for the 6178 tons of new decentralized chillers	$617,720

Table 5.6 The Estimation of Initial Cost of the Chilled Water System for Individual buildings (Reproduced from Central Campus Chilled Water Plant Feasibility Study, Van Boerum & Frank Associates, Inc., 2007)

Proposed New Central Chilled Water Plant			
Electrical Cost (2320 tons)	**Annual Electric Consumption (kw-hrs)**		**Total Costs**
Chiller Totals	1,209,600	0.048$/kwh	$58,061
Pump Totals	425,091	0.048$/kwh	$20,404
Cooling Tower Totals	148,643	0.048$/kwh	$7,135
		Subtotal	$85,600
Maintenance Cost			
U of U personnel	0.25 man-years	$60,000/year	$15,000
Vendor Maintenance	2,320 tons	$6.50/ton/year	$15,080
		Subtotal	$30,080
		Existing Distributed Chiller Annual O&M Costs	$115,680
		Cost/ton/year	$49.86
Estimated cost per year for the 6178 tons of new decentralized chillers			$308,048

Table 5.7 The Estimation of Initial Cost of the New Central Plant (Reproduced from Central Campus Chilled Water Plant Feasibility Study, Van Boerum & Frank Associates, Inc., 2007)

In Table 5.6, the subtotal of electric costs for each year is $104,770, while this value in Table 5.7 is $85,600. This shows nearly a 20% the energy cost savings in operation when the utility centralized chilled water design is used. In Wang and Zhao's report on the utility centralized chilled water system design for the Guangzhou University area, it is also noted that if the university could cultivate an experienced team to operate the system, it was possible to achieve 20% energy cost savings by using the utility centralized chilled water systems for individual buildings (2003).

Another source of cost savings that is shown in these tables is maintenance cost. These cost savings have two components. The first is the reduction in the number of people required to maintain the equipment. As the total amount of equipment, including chillers, cooling towers, and pumps is reduced, the number of people that the system requires for maintenance decreases. In Table 5.6, the required unit number of people for maintenance averages 1.25 per year for a chilled water system for individual buildings. In Table 5.7, this number changes to 0.25 per year for the centralized design. The second source of maintenance cost savings is the reduction in required vendor maintenance. Because the utility centralized chilled water system requires less equipment, and the equipment is placed in the same location, the cost of the vendor maintenance is lower. The vendor maintenance cost in Table 5.6 is $22.50 per ton per year while this number in Table 5.7 is reduced to $6.50 per ton per year.

In China, labor costs are lower than they are in the United States, so the maintenance cost savings are a smaller portion of the total cost savings for the utility centralized chilled water system. However, the cost savings associated with choosing the utility centralized chilled water system are still viable. Combined with the operation cost savings, the reduction of the O&M cost saving will still be significant.

According to the data discussed above, the utility centralized chilled water system can provide a large amount of cost savings when applied to urban areas compared to using centralized chilled water systems in individual buildings.

Chapter 6 - Additional Advantages of Utility Centralized Chilled Water System

Since the preceding chapters did not cover all the advantages of the utility centralized chilled water system, this chapter will explain some additional advantages that the Chinese government will need to consider. Besides the potential cost savings, other factors are also important when engineers determine whether the utility chilled water system should be chosen. This chapter will discuss these factors.

Energy Consumption Reduction

Energy consumption not only determines the operation costs of the system, but it also has an important effect on the environment. China faces daunting challenges in terms of environmental protection. Its huge population requires significant energy generation, and this problem will worsen because the Chinese government has decided to accelerate rural to urban development in the next few years. According to the National Plan on New Urbanization published by the Central Committee of the Communist Party of China (CPC) and the State Council of China in 2014, the Chinese government aims to provide urban living conditions to 234 million rural people before 2020. Consequently, energy consumption and production is a serious problem that the Chinese government needs to address.

The most serious problem arising from such significant energy consumption is the amount of carbon dioxide that will be emitted. China is the largest carbon dioxide emitting country in the world, and its motor vehicles, factories, power plants, and boilers released 29% of the world's total carbon dioxide emissions in 2013 (Chris, 2015). In Chapter 1, it was noted that China has promised to cut its carbon dioxide emissions to 45% before 2020. Although there is no doubt that China can achieve this goal before 2020, the Prime Minister Li Keqiang of China has announced a new goal, which extends this cut to between 60% and 65% compared to the 2005 level, before 2030. On the other hand, the chief means of producing electricity is through burning coal, and this will increase the carbon dioxide emissions greatly. According to the National Energy Administration of China, the amount of electricity produced by coal is 758 million kWh, which constituted 66.2% of the total electricity generation in 2012. Therefore, it is very important for the Chinese government to choose centralized chilled water systems that consume less energy.

In Chapter 5, the utility centralized chilled water system showed approximately 20% electricity cost savings compared to using chilled water system for individual buildings. These cost savings are based on overall energy savings. In Table 5.6, the energy use of the chillers from individual buildings is 1,749,785 kWh/yr, while utility centralized chilled water systems only use 1,209,600 kWh/yr as shown in Table 5.7. The chiller energy consumption reduction is 540,185 kWh/yr. The reduction occurs because the utility centralized chilled water system uses equipment such as chillers and cooling towers that consume less energy. Although the pumping electricity consumption from the utility centralized chilled water system is much higher than the consumption from pumping in the chilled water system for individual buildings, the pumping electricity consumption increase will be offset by the chiller energy consumption reduction. The pumping electricity consumption in Table 5.6 is 255,202 kWh/yr, while this number is 425,091 kWh/yr in Table 5.7. The increase is 169,889 kWh/yr, which is smaller than the chiller energy consumption reduction. The approximate 20% electrical energy savings can make a big contribution to China’s sustainable development because the electricity is mainly produced by using coal in China. Table 6.1 shows the different sources of power used to produce electricity.

Year	2007	2008	2009	2010	2011	2012	2013	2014
As Percentage of Total Energy Production (%)								
Coal	77.8	76.8	76.8	76.2	77.8	76.2	75.4	73.2
Crude Oil	10.1	9.8	9.4	9.3	8.5	8.5	8.4	8.4
Natural Gas	3.5	3.9	4.0	4.1	4.1	4.1	4.4	4.8
Primary Electricity and Other Energy	8.6	9.5	9.8	10.4	9.6	11.2	11.8	13.7

Table 6.1 Different Sources of Power Consumption as Percentage of Electrical Energy Production in China (Data Source from China Statistical Yearbook 2014)

According to Table 6.1, the amount of electricity produced by coal has gradually decreased since 2007. However, it still accounted for 73.2% of fuel sources used to produce the electricity in 2014. When electrical energy consumption is reduced, coal consumption will be reduced. Therefore, the reduction in electrical energy consumption from the utility centralized chilled water system is very important.

Reliability

Another benefit of applying the utility centralized chilled water systems instead of chilled water systems for individual buildings is their reliability. Both utility centralized and chilled water systems for individual buildings experience some uncertainty during their operation. However, those uncertainties influence utility centralized chilled water systems less frequently. This is based on the system-wide redundancy that utility centralized chilled water systems provide, which means that if there is a problem in one chiller or pump, the cooling load can be shifted to another one. To achieve this goal, the system requires plenty of space, but the chilled water system in an individual building usually does not have flexibility, at least not at a reasonable cost. Because the utility centralized chilled water system has a greater capacity for thermal storage and redundancy, enough time exists to replace a chiller if the need arises. Therefore, the utility centralized chilled water system is more reliable. The Figures 6.1 and 6.2 show how the reliability of each of these systems compare.

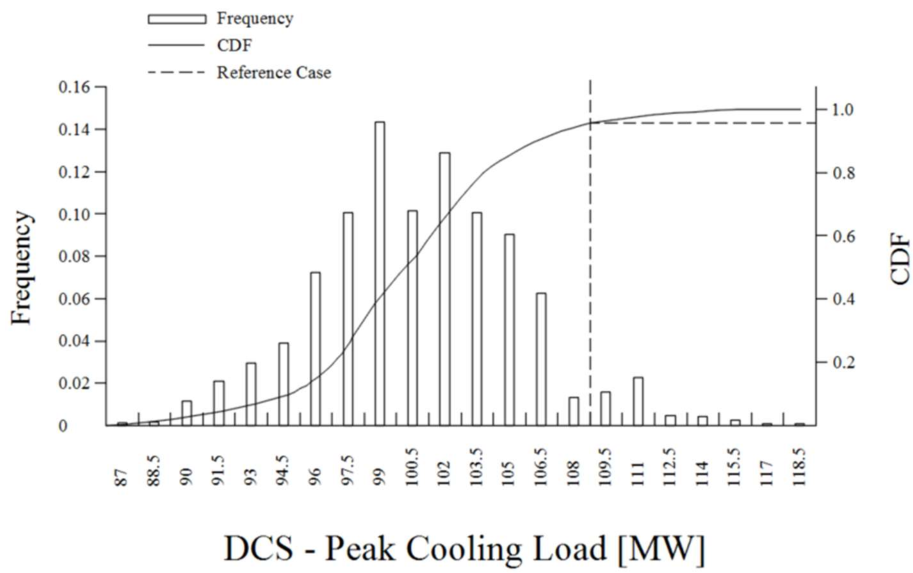


Figure 6.1 Peak Cooling Load Distribution of the DCS (Reproduced from Robust Optimal Design of District Cooling Systems and the Impacts of Uncertainty and Reliability, Wenjie Gang, 2016)

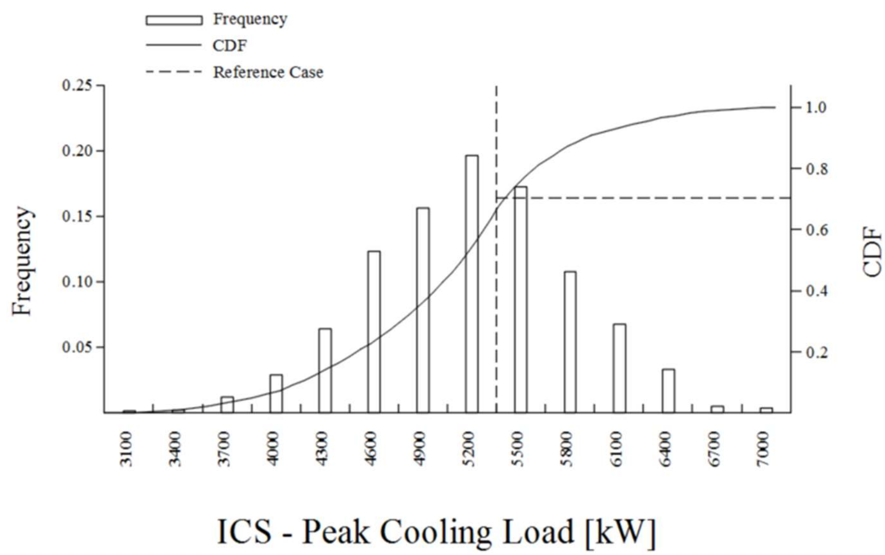


Figure 6.2 Peak Cooling Load Distribution of the ICS (Reproduced from Robust Optimal Design of District Cooling Systems and the Impacts of Uncertainty and Reliability, Wenjie Gang, 2016)

Figures 6.1 and 6.2 represent data from a case study project in the Kwu Tung North area in the North East New Territories region of Hong Kong. DCS is the district cooling system, or the utility centralized chilled water system. ICS is the individual cooling system, which is the chilled water system in individual buildings. CDF is the cumulative distribution function. Figure 6.1 shows that the peak cooling load of the DCS has a high frequency between 98MW and 105MW, which means it has a high probability of failing in this range. The relative difference is using the difference between the reference case and start or end number versus the reference case number, which generally indicates the reliability of the system. The DCS's relative difference compared with the reference peak cooling load is between -21% and 9%. The peak cooling load of ICS has a high frequency between 4600kW and 5500kW, and its relative difference compared with the reference peak cooling load is from -44% to 30%. Usually, the reference peak cooling load of the system should be over 90% of the CDF to avoid the uncertainty factors. Compared to the individual building cooling system, the district cooling system has a much lower relative difference with respect to the reference peak cooling load. In other words, the uncertainty will have less impact on the district cooling system's reliability. Therefore, the utility centralized chilled water system is more reliable than the chilled water system for an individual building.

Urban Development

The utility centralized chilled water system is also better suited to urban development in China. In the past seven years, the Chinese government has set up about fifteen "National New Areas," which are new urban areas close to significant cities to achieve its "rural to urban" development plan. The construction of the new urban areas results in a high level of employment. More importantly, it can solve the excess material capacity problem that China is facing right now. According to China's national report on the industry, the quantity of steel on hand showed an excess capacity of more than 30% and for concrete, more than 20%, in 2005. The report also showed that the problem would become even worse. Therefore, the Chinese government has begun to reduce the steel and concrete production capacity. The excess capacity is a complex societal problem that cannot just be solved by closing factories. In this case, how excess products are used is very important. The construction of the utility centralized chilled water system can solve part of this problem because the construction of the utility centralized chilled water systems require a large amount of concrete and steel. Table 6.2 is a financial estimate concerning the proposed district cooling system in Hong Kong.

1) DCS Plants	$ million
Civil Works	422.0
Electrical and Mechanical Works	464.0
2) Mains Laying	279.0
3) Connection Facilities at User Buildings	54.0
4) Environmental Mitigation Measures	10.0
5) Consultants' Fee for Contract Administration	9.0
6) Resident Site Staff Cost	41.0
7) Contingencies	123.0
8) Provision for Price Adjustment	269.0
Total	1,671.0

Table 6.2 Cost Estimation of the Kai Tak Development Project in Hong Kong

(Data Source from Legislative Council, Agenda for Public Works Subcommittee Meeting PWSC (2009-10) 24, District cooling system at the Kai Tak development)

As shown Table 6.2, the district cooling system, or the utility centralized chilled water system, requires 422 million dollars for civil works and 279 million for mains laying, which requires 25% and 17% of the total prices. This shows that there will be plenty of required construction related to the district cooling system, further relying on the steel and concrete industry. What's more, the district cooling system can also be applied to replace the existing aged individual building systems in the old urban area. The future prospects for the utility centralized chilled water system should be bright.

It must be emphasized that this is an example in an already developed urban environment. There will be a more cost-effective implementation in newly developed environments. In the developed urban areas, different types of cooling systems in buildings already exist. The systems in those buildings need to be replaced. Therefore, the cost in the developed urban areas will be greater than the newly developed areas.

Chapter 7 - Recommendations and Conclusion

Finally, recommendations about the application of utility centralized chilled water system, or the district cooling, for densely populated urban areas in China, will be made in this chapter. Included will be a summary of findings on the potential cost savings, energy consumption reduction and reliability of the centralized chilled water system.

Recommendations

The utility centralized chilled water system is a new technique in the Chinese air conditioning market. It has been shown the utility centralized chilled water system has advantages with respect to cost savings, energy consumption reduction, reliability, and its ability to adapt to urban area installations. However, the climate of different locations has a significant impact on the cost savings. In this case, figuring out the appropriate application for a utility centralized chilled water system is very important.

Recently, the Chinese government has started to construct a district cooling system for an urban area in one of its "National New Areas," the Hengqin Free Trade Zone. Although this project will provide detailed data about cost savings in the south of China, the Chinese government should encourage more district cooling systems in some other "National New Areas" located in the middle and north of China to obtain accurate group data and perform a comparative analysis. Additional and more accurate results will be derived after installing and documenting other systems.

On the other hand, the Chinese government should start trying to replace the unitary system or chilled water systems for individual buildings with the centralized utility system in one or two old urban areas. Some authors suggest this because China has many historical cities and urban planning in those areas differs from planning the new urban areas. For the purpose of historical protection, chilled water systems cannot be applied to historical buildings because of aesthetics or structural problems. The extent to which the utility centralized chilled water system can also be applied should be based on data from newly constructed projects.

Another problem the Chinese government needs to take into consideration is how to apply the utility centralized chilled water system to residential buildings in the urban areas. A majority of people living in the residential buildings have used the unitary HVAC systems more than twenty years, and, therefore, it will be difficult for them to accept a new type of air conditioning system. However, if the new air conditioning systems can provide low utility costs, customers will accept them more easily because this type of air conditioning system can ensure a better indoor environment compared to the unitary air conditioning system. However, to solve this problem, the practical data should be metered. Also, other information, such as the practical initial cost and O&M cost, should be based on practice. Therefore, this problem also indicates that the Chinese government should set up more district cooling systems in different cities to gain more experience as soon as possible.

Conclusion

Based on the data presented, the utility centralized chilled water system, or district cooling is a more suitable choice compared to using the chilled water production in individual buildings and the DX based unitary systems in China.

Unlike the unitary air conditioning system, which is widely used in the residential areas in China, the centralized chilled water system in individual buildings with air-handling units or fan-coil units can provide residents better indoor air quality. It has a much better $PM_{2.5}$ control, a factor related to health that Chinese residents pay more attention to today. Moreover, the energy consumption will be lower because of the higher equipment efficiency performance. As a consequence, the life cycle cost for the user is possibly reduced. Compared to these advantages, disadvantages such as its more complex installation and the requirements of more floor space can be ignored because these problems can be easily solved during the new building construction process. As the utility centralized chilled water system has the same air delivery system as the centralized chilled water system in individual billings, the utility centralized chilled water system is also better than the unitary air conditioning system in China.

Second, evidence indicates that the utility centralized chilled water system can provide lower initial, and operation and maintenance costs than the chilled water systems for individual buildings. Even though China has lower labor costs than the United States, the initial and O&M cost savings will still be significant in China. Utility centralized chilled water systems also consume approximately 20% less energy than chilled water systems in individual buildings. This advantage will help the Chinese government achieve its goal of carbon dioxide emission reduction. Additionally, utility centralized chilled water systems are more reliable than the current systems, and this is critical for commercial buildings such as hospitals and office buildings.

The utility centralized chilled water system is best suited for sustainable development in China. It can significantly aid in reducing energy consumption in densely populated urban areas and provide citizens with a better indoor environment. Equally important, construction in both new and existing urban areas can provide jobs and solve the steel and concrete excess supply problems because the construction of utility centralized chilled water systems require large amounts piping distribution. As long as the Chinese government can train experienced design, construction, and O&M teams, the utility centralized chilled water system should be appropriate in areas in China where the climate is similar to the climate in Utah, or the cooling requirements are greater than those in Utah. Consequently, the utility centralized chilled water system, or the district cooling system should have a bright future in China.

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